The Quantum Echo of the Early Universe

Mercedes Martín-Benito

Radboud University Nijmegen

in collaboration with
Ana Blasco (UCM), Luis J. Garay (UCM/IEM-CSIC),
Eduardo Martín-Martínez (IQC-UW/PI)

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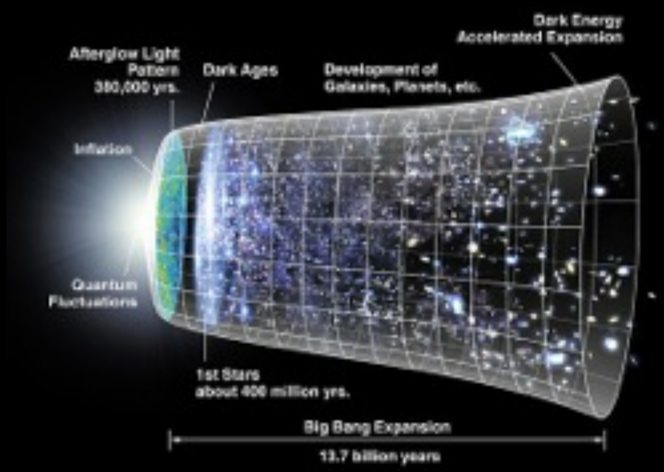
Looking for Signatures of QG today

- To test proposals for Quantum Gravity we need
  - i) predictions
  - ii) experimental data encoding QG effects

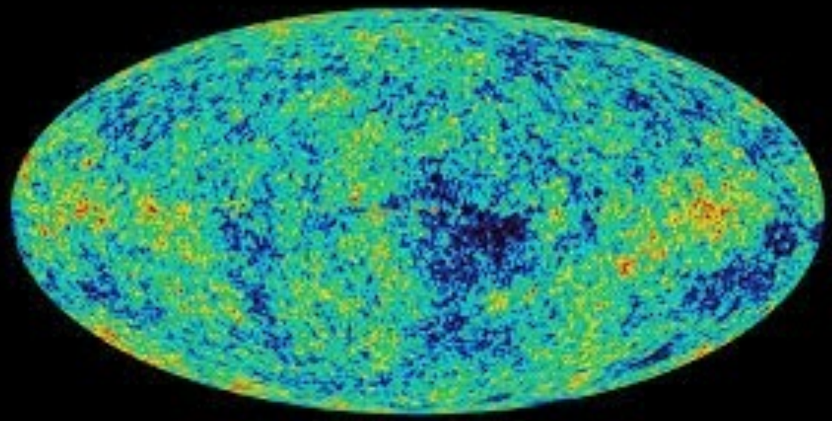
- QG scales out of reach of experiments on earth

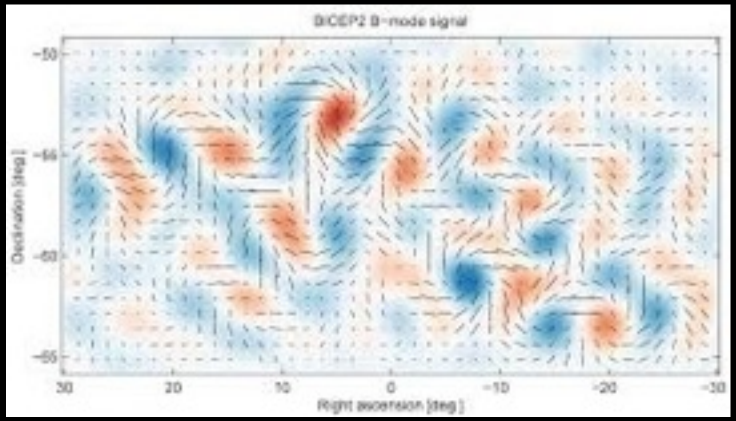
- Most promising window: COSMOLOGY



Looking for Signatures of QG today

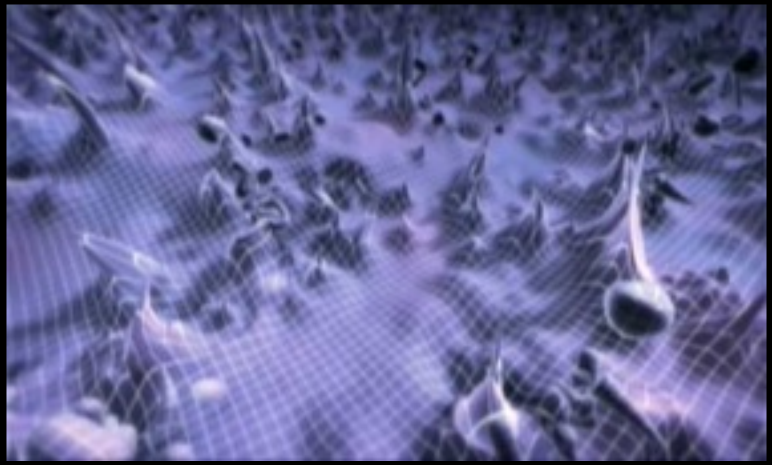
- Evidence of early Universe physics imprinted onto the CMB





"The long search of B-modes is apparently over and a new era of B-mode cosmology has begun"

- Primordial gravitational waves carry information of the quantum fluctuations of the geometry of the early Universe



Looking for Signatures of QG today

- Have QG signatures really survived from the early Universe all the way to our current era?

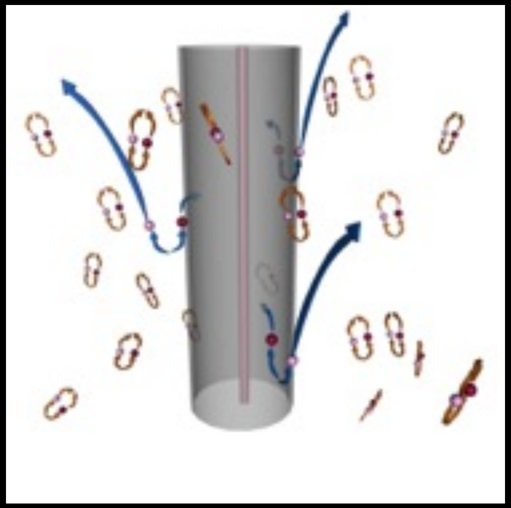
- If so, how strong are they?

- Will it be possible to validate or falsify different QG proposals by looking at the data?

We explore a simple way, based on a toy model, to assess the strength of the quantum signatures of the early Universe that might be observed nowadays

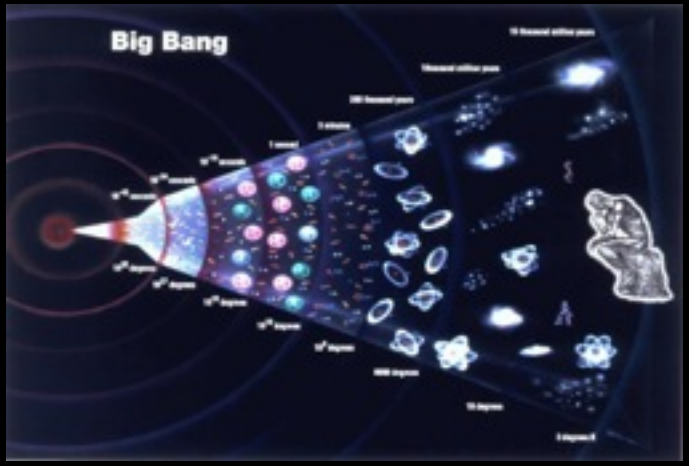
Setting

- We will analyze Gibbons-Hawking effect : Creation of particles measured by a particle detector due to cosmological expansion when the surrounding matter fields are in vacuum



- Particle detector coupled to matter fields from the early stages of the Universe until today:

Would the detector conserve any information from the time when it witnessed the very early Universe dynamics?



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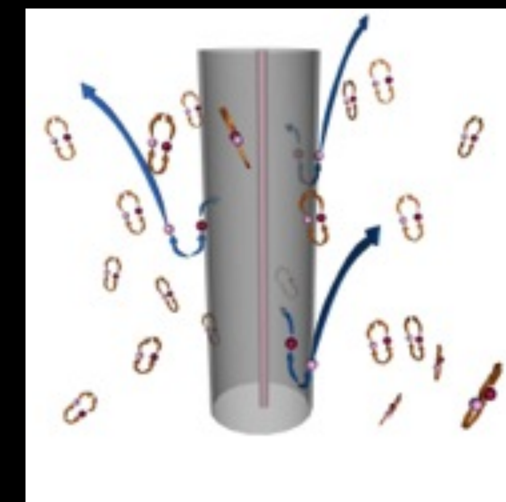

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YES

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Early Universe dynamics

- Flat FRW with T3 topology and matter source a massless scalar φ

- We will compare the response of the detector evolving under two different Universe dynamics which disagree only during the short time when matter-energy densities are of the order the Planck scale

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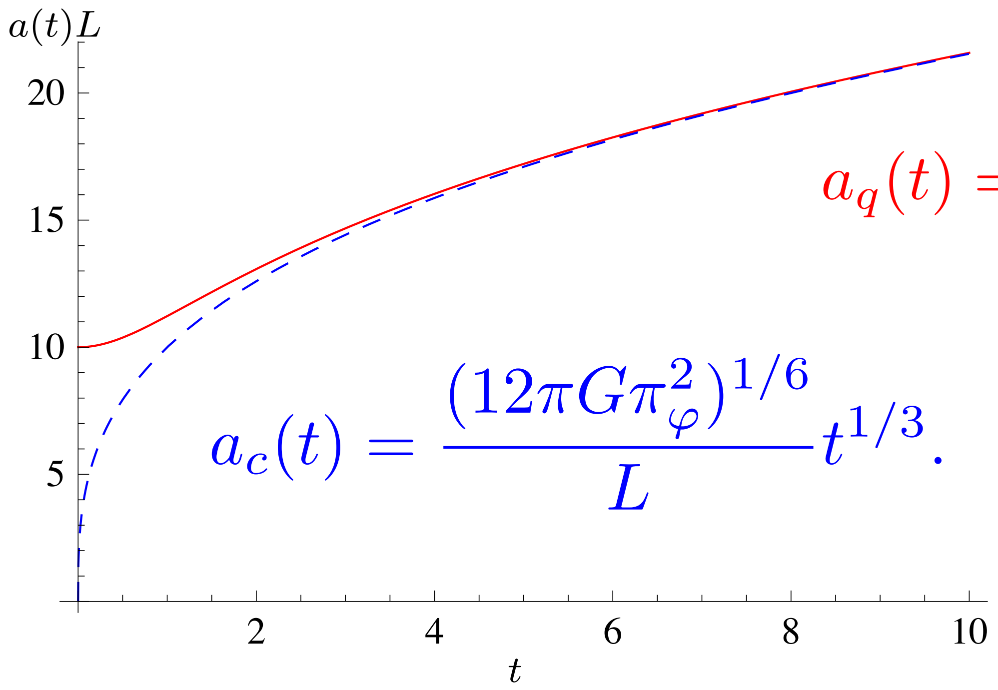
GR vs Effective LQC



$$a_q(t) = \frac{l}{L}\left(\frac{\pi_\varphi^2}{12\pi G}\right)^{1/6}\left[1+\left(\frac{12\pi G}{l^3}\right)^2 t^2\right]^{1/6}.$$

$$a_c(t) = \frac{(12\pi G \pi_\varphi^2)^{1/6}}{L} t^{1/3}.$$

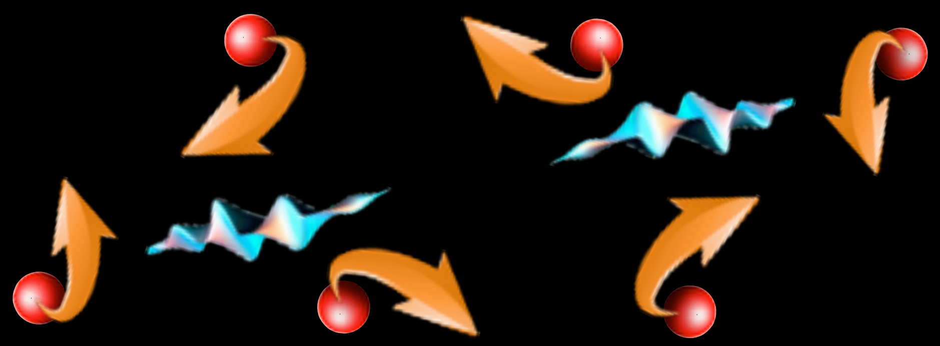
l ~ quantum of length

L ~ compactification scale

Gibbons-Hawking effect

- We consider a massless scalar field ϕ in the conformal vacuum

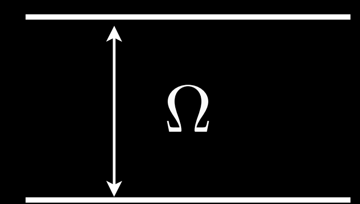
- The proper time of comoving observers (who see an isotropic expansion) does not coincide with the conformal time



$$\eta_c(t) = \frac{3L\, t^{2/3}}{2(12\pi G \pi_\varphi^2)^{1/6}}$$

$$\eta_q(t) = \frac{L}{l}\left(\frac{12\pi G}{\pi_\varphi^2}\right)^{1/6} t \cdot {}_2F_1\left[\frac{1}{6}, \frac{1}{2}, \frac{3}{2}, -\left(\frac{12\pi G}{l^3}t\right)^2\right] \underset{t \gg l^3/(12\pi G)}{\longrightarrow} \eta_c(t) + \beta$$

The Unruh -De Witt model



$|e\rangle = \sigma^{+}|0\rangle$

$|0\rangle = \sigma^{-}|e\rangle$

$$\hat{H}_I(t) = \lambda\, \chi(t)(\sigma^{+} e^{i\Omega t} + \sigma^{-} e^{-i\Omega t})\hat{\phi}[\vec{x}_0, \eta(t)]$$

t	**proper time of the detector (comoving)**
λ	**coupling strength**
$\chi(t)$	**switching function**
$[\vec{x}_0, \eta(t)]$	**world-line of the detector (stationary)**

Probability of excitation

- T_0 : field in the conformal vacuum and detector in its ground state

- Transition probability for the detector to be excited at time T :

  At leading order (λ small enough)

$$P_{\mathrm{e}}(T_0, T) = \lambda^2 \sum_{\vec{n}} |I_{\vec{n}}(T_0, T)|^2 + \mathcal{O}(\lambda^4)$$

$$I_{\vec{n}}(T_0, T) = \int_{T_0}^{T} \mathrm{d}t \frac{\chi(t)}{a(t)\sqrt{2\omega_{\vec{n}} L^3}} e^{-\frac{2\pi i \vec{n}\cdot\vec{x}_0}{L}} e^{i[\Omega t + \omega_{\vec{n}}\eta(t)]}$$

$$\vec{n} = (n_x, n_y, n_z) \in \mathbb{Z}^3 - \vec{0} \qquad\qquad \omega_{\vec{n}} = \frac{2\pi}{L}|\vec{n}|$$

Probabilities: GR vs effective LQC

- **Difference of probabilities** $\Delta P_{\rm e}(T_0,T)\equiv P_{\rm e}^{q}(T_0,T)-P_{\rm e}^{c}(T_0,T)$

- **We split the integrals**

$$I^c_{\vec{n}}(T_0,T)=I^c_{\vec{n}}(T_0,T_m)+I^c_{\vec{n}}(T_m,T) \qquad \eta_q(T_m)\approx\eta_c(T_m)+\beta$$

$$I^q_{\vec{n}}(T_0,T)=I^q_{\vec{n}}(T_0,T_m)+e^{i\omega_{\vec{n}}\beta}I^c_{\vec{n}}(T_m,T)$$

$$\boxed{\begin{aligned}\Delta P_{\rm e}(T_0,T)=\lambda^2\sum_{\vec{n}}\Big[&\left|I^q_{\vec{n}}(T_0,T_m)\right|^2-\left|I^c_{\vec{n}}(T_0,T_m)\right|^2\\ &+2{\rm Re}\Big(I^{c\,*}_{\vec{n}}(T_m,T)\left[e^{-i\beta\omega_{\vec{n}}}I^q_{\vec{n}}(T_0,T_m)-I^c_{\vec{n}}(T_0,T_m)\right]\Big)\Big]\end{aligned}}$$

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The relative difference on the detector's particle counting in both scenarios will be appreciably different even for long T

Sensitivity with the quantum parameters

- Any observations we may make on particle detectors will be averaged in time over many Planck times

$$\langle P_{\mathrm{e}}(T_0,T)\rangle_{\mathcal{T}} = \frac{1}{\mathcal{T}}\int_{T-\mathcal{T}}^{T} P_{\mathrm{e}}(T_0,T')\,\mathrm{d}T' \qquad \mathcal{T} \gg l^3/(12\pi G)$$

- Sub-Planckian detector $\Omega \ll 12\pi G/l^3$

- Estimator to study sensitivity with quantum of length

$$E = \left\langle \frac{\langle \Delta P_{\mathrm{e}}(T_0,T)\rangle_{\mathcal{T}}}{\langle P_{\mathrm{e}}^{\mathrm{GR}}(T_0,T)\rangle_{\mathcal{T}}} \right\rangle_{\Delta T}$$

$$\Delta T = T - T_{\mathrm{late}}$$

$$\Delta T,\ T_{\mathrm{late}} \gg l^3/(12\pi G)$$

Sensitivity with the quantum parameters

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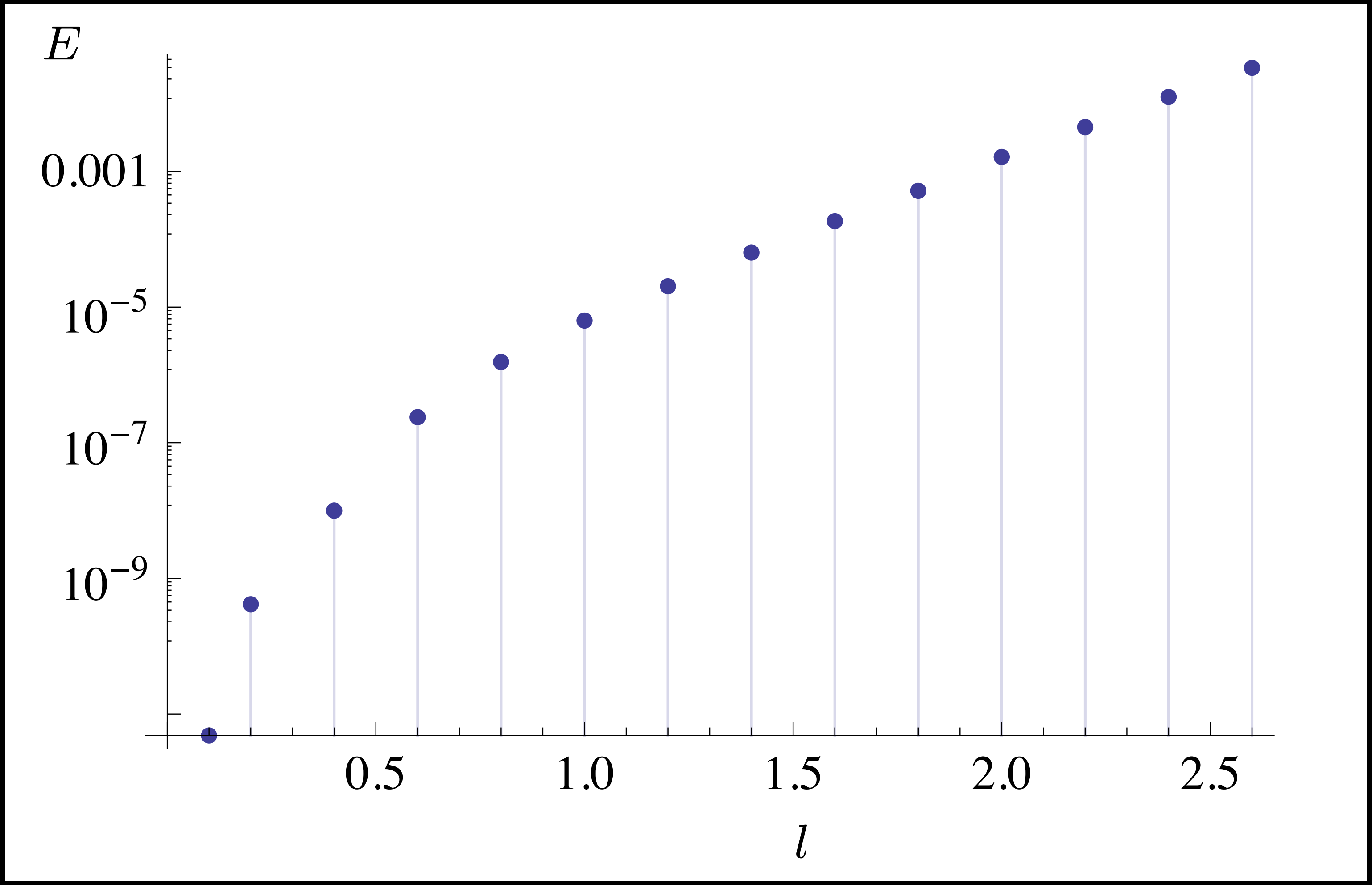

Exponential with the size of the spacetime quantum

- Cosmological observations could put stringent upper bounds to l

Conclussions

- Although this is a toy model, it captures the essence of a key phenomenon: Quantum field fluctuations are extremely sensitive to the physics of the early Universe.

- The signatures of these fluctuations survive in the current era with a significant strength.

- We showed how the existence (or not) of a quantum bounce leaves a trace in the background quantum noise that is not damped and would be non-negligible even nowadays.

- The use of LQC in this derivation is anecdotical, and we believe that our main result is general:

The response of a particle detector today carries the imprint of the specic dynamics of the spacetime in the early Universe

Thanks for your attention!